III

THE STRUCTURE OF THE UNIVERSE

IT MAY SEEM, at first sight, presumptuous to attempt the discussion, in one hour or less, of such a comprehensive topic as the structure of the universe. Actually the subject is not as big as it sounds. There are, in one sense, as many universes as there are individuals; but the universe in this personal sense will be ruled out of the present discussion. A tremendous simplification is at once achieved when we limit our topic to the physical universe. We now inquire, what is the physical universe?

Eddington has defined it as the "theme of a specified body of knowledge, just as Mr. Pickwick might be defined as the hero of a specified novel." Such a definition emphasizes the epistemological point of view and therefore it suffers from lack of definiteness and simplicity. There is beautiful directness and decisiveness in the attitude of the mathematician who wrote an equation on one line in one of his published papers and said, "This equation contains everything we know about the physical universe." The conciseness of the language of mathematics is probably nowhere better exemplified than in this equation. On the other hand, the universe, if it can be described in terms of mathematical symbols and with one equation, may not seem like such a big subject after all.

To the physicist, matter, space, and time exist outside the human mind. The physical universe is an objective, dynamic arrangement of all matter, space, and time. In discussing the structure of the universe we merely attempt to describe some of the features of this arrangement.

Before beginning such a description it seems necessary to indicate just how it is related to human welfare—since the general title of this series of lectures is "Science and Human Welfare." I am venturing to interpret the phrase "human welfare" in the broadest possible sense. There are many types of scientific investigation which do not appear to have any direct bearing on the pleasures or pains of the human race. The discovery of the planet Pluto cannot be said to have done very much towards raising the sum total of human welfare, in the ordinary sense. But in the broadest sense, it may be said that the welfare of a nation is closely tied up with the capacity of that nation for untiring search after truth. Intellectual unrest, intellectual curiosity is, we like to think, essential to the true growth and development of a people. A dairy company advertises that its milk comes from contented cows. A rival company is perhaps more progressive in its views when it advertises that its cows are not contented—they are always trying to do better.

The thesis is, then, that the pursuit of pure knowledge is indicative of a healthy national mind; that full development of intellectual activity, whether it be in the matter of investigating the stars or in building a better radio, is essential to the true welfare of a nation. The Russians asked a captured Nazi why he came into their country. He replied, "I am just a little man, I do what the Führer says." A nation is facing tragedy when free speculation is discouraged, when science is devoted solely to control of men and machines and to the production of a workable mass of "little men."

To begin this discussion of matter, space, and time we will try first to systematize our ideas of space, or size, in relation to matter. Imagine a long, horizontal line drawn so as to represent "the x-axis." Let all objects in the universe be placed along this line in the order of their sizes. The smallest objects will be placed near the beginning of the line,

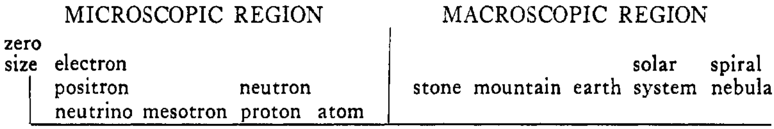

FIG. 1

at its left end. Larger and larger objects will be placed farther and farther to the right. We next divide the line into two parts by a vertical line. All objects to the left of this vertical line are too small to be seen with the naked eye, so this region is called the *microscopic* region. In it are placed different kinds of particles such as molecules, atoms, the proton, the neutron, the mesotron, the electron, positron, and neutrino. These particles are placed nearer and nearer to the origin of the line as they become smaller and smaller. It is worth noting that nature seems not to have given us anything smaller than the electron, in spite of the fact that there is plenty of room for particles between the electron and the origin of the line.

To the right of the vertical dividing line we place all objects large enough to be seen with the naked eye. This region is called the *macroscopic* region. We might put in here, stones, mountain, earth, solar system, spiral nebulae. The farther end of the macroscopic region may be given a special sub-title, the *astronomical* region.

We have arranged here various matter elements in a certain spatial relationship. The time concept is involved because this is an arrangement which may be correct only at one instant of time. It is possible that the position of some of these entities on the line is constantly changing. When an electron gets into rapid motion its mass is changed a little and it shortens one of its dimensions. It thus shifts its position on the line slightly to the left whenever it has a high velocity. The solar system may be slowly running down so that the planets gradually approach the sun. If this is the case the position of the solar system on the line is slowly shifting to the left.

Certain segments of this line have occupied the attention of various specialists. Astronomers deal with everything listed to the right of earth. Thousands of specialists work on the section from earth to atom. Physicists in recent years have concentrated intensively on the segment from atom to zero. The discovery of the positron, the neutron, the mesotron, within the last decade, has opened up a most fruitful field of research in physics. In this region, forever beyond the reach of the human eye, is probably contained most of the mystery of the entire universe. As K. K. Darrow has expressed it, "This field is unique in modern physics for the minuteness of the phenomena, the delicacy of the observations, the adventurous excursions of the observers, the subtlety of the analysis, and the grandeur of the inferences."

It is not too much to say that if some American physicist could only make the right kind of discovery in this domain our entire oil and coal industries would become more or less obsolete and World War II would be won in a matter of days. It should also be said that such a discovery is possible but not probable.

Returning now to our linear layout for the universe we may note that everything to the right of proton is constructed out of the material included in the range from proton to zero. All matter in the universe exists in the form of bunches or aggregates of smaller parts. Protons, neutrons, electrons bunch to form atoms; atoms group into molecules; molecules

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FIG. 2. The spiral nebula M 51 in Canes Venatici.

group into stones and mountains; stones and mountains form the earth. In the astronomical field, planets group about the sun to form the solar system—a solar system which in the astronomical field is remarkably like the atom in the microscopic field.

The important unit of structure in the astronomical field is a sun. Practically all of the stars which we can see on a clear night are distant suns, much like our own, although it is thought that only an extremely small fraction of these suns have planets around them like our own.

All of these suns which can be recognized distinctly are grouped in a sort of flattened, disk-like bunch which is whirling in empty space. Our own sun and planetary system is a member of this group, being located about 30,000 light-years[1] distant from the center, or hub, of this gigantic disk. When we look into space along the plane of the disk the stars seem to be distributed very densely. We see the milky way. This bunch of suns is called a spiral nebula. It is sometimes called a galaxy, or an island universe. The word "universe" in this sense has a restricted meaning because our island universe is not the only one in existence. There are millions of others distributed throughout space as far as our most powerful telescopes have been able to penetrate.

The nebulae are by no means recent discoveries. Sir William Herschel, 150 years ago, suspected that they were distant groups of stars. The philosopher Kant believed that they were "systems of many stars, whose distance presents them in such a narrow space that the light which is individually imperceptible from each of them, reaches us, on account of their immense multitude, in a uniform pale glimmer." They have been described as looking like "candle-

[1]A light-year is the distance which light travels in one year. It is approximately 6,000,000,000,000 miles.

light seen through horn." A rough diagram, not drawn to scale, is given in Fig. 3 to indicate the total extent of the

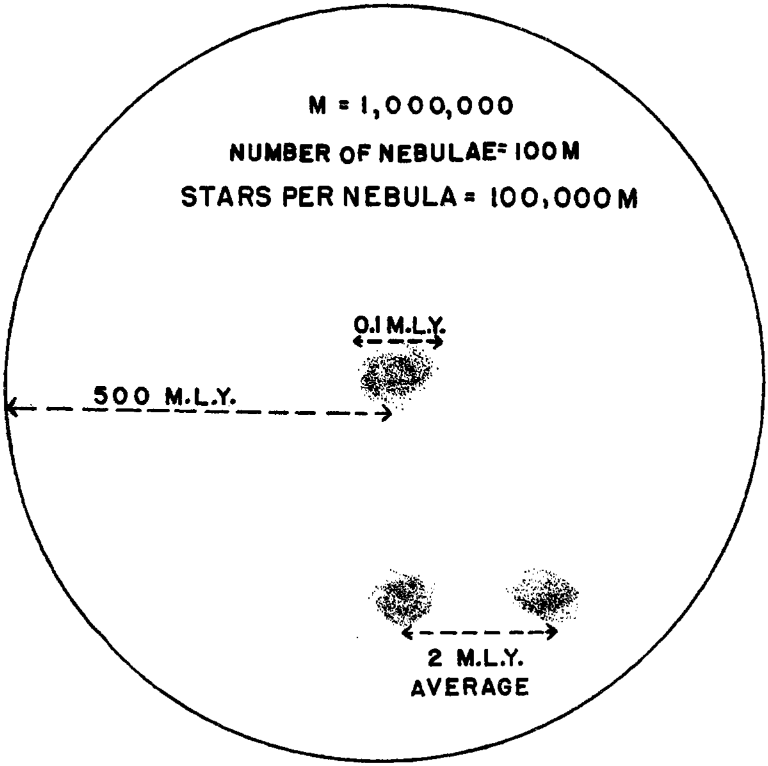

FIG. 3. Sphere of view of the 100-inch telescope. Distances are in light years, L.Y., and the diagram is not to scale. Our earth is about 30,000 L.Y. away from the center of the central nebula above.

entire universe which has been observed, up to the present, with our most powerful telescopes.

We might now indicate on the linear layout of Fig. 1 the approximate size of the largest bunch of matter, the spiral nebula, as 100,000 light-years. Also we might speculate as to the possibility of nebulae themselves forming still larger groups. Extensive surveys have been made by the astronomers at Harvard and Mount Wilson, of the distribution in space of the nebulae, and there is, indeed, evidence of grouping of nebulae. It is legitimate to add another bunch of matter to the line layout—the super-nebula, or super-galaxy.

The super-galaxy is the largest known aggregation of matter in the universe. Its diameter may be of the order of a million light-years. At least that is the estimate made by Harlow Shapley of the diameter of the group of nebulae in which our own is located. Our local group contains perhaps 15 or 20 nebula, but in some super-galaxies there are hundreds of members.

So far, then, our picture of the universe reveals a granular, or atomic structure. We start near the zero point of size, with a particle of definite size. A fundamental law of attraction operates to cause the small particles to group together to form larger particles, these larger particles again group to form still larger particles, and so on until we reach the limit of observation, the enormous super-galaxy. We are unable to put a stop at the right hand end of our line, as we have done at the left end. Space may go on into infinity—possibly matter may go on bunching up into larger and larger aggregates with no limit as to the ultimate size of any final bunch, because there may never be any final bunch. Speculations of this kind may be interesting but they are not of much significance, otherwise, because they take us outside the realm of possible human experience.

It seems probable that in detecting the super-galaxy man has reached the limits of observation in his probing of the depths of space. The new 200-inch telescope will be doing a fine job in helping to chart and analyze these enormous groups of matter.

The line diagram of the universe, limited at one end by the electron, at the other by the super-galaxy, has given a rather simple picture in terms of two variables, space and matter. The third variable, time, must now be considered. We have to consider the relationship between the various units of our structure as this relationship may change from time to time. Newton's Law of Universal Gravitation says that every particle of matter in the universe attracts every other particle. If forces of attraction cause matter to bunch up into aggregates of various sizes why may not the various bunches themselves start coming together until eventually there results just one large, static bunch of matter floating quietly in an infinity of space? Such an end result seems logical, but it cannot happen until the kinetic energy of matter, the energy of motion, has been converted into radiation and transferred to infinity. Such a transfer of energy appears, in fact, to be going on.

A study of the motions of the various aggregates may be expected to throw some light on this question. We start with the smallest particles, electrons, for example. In addition to random motions caused by collisions with other particles, all electrons are supposed to spin. They may be thought of as being like tops which never run down. When an electron helps to form an atom, in addition to spinning it also revolves about the nucleus, just as the earth revolves about the sun. The aggregations of matter between atom and earth on the diagram of Fig. 1 may have various kinds of motion but when earth is reached we again have the spin about an axis and the revolution about the sun. Our sun, together with all the other suns in its group, forms a nebula which spins with high speed about a central axis. The spin velocity is very high, but the size of our nebula is so great that it takes about two million centuries for it to make one revolution. As Shapley puts it, this is the time required to "click off one cosmic year."

The motion of the super-nebula is not known in accurate detail. It is possible that some sort of gigantic spin is present here also, but so far such a spin has not been detected. Instead, a very surprising sort of motion has been discovered, a motion which is just contrary to what we expect if matter is to agglomerate into one big bunch. The super-nebulae appear to be receding from us. The super-nebula to which our galaxy belongs maintains its fixed dimensions, and behaves more or less as a unit, but all the other super-nebulae appear to be flying away from ours with high speeds. The farther away from us they are, the faster they seem to recede. There seems to be no good way of explaining such a phenomenon. One might assume that a primeval explosion started all matter out in all directions from an original concentration, but there are serious difficulties involved in such a theory.

The whole question of the expanding universe is definitely controversial. The consequences of accepting or rejecting the theory are so great that it will be worth while to review briefly the evidence.

Suppose the lights of a very distant city are observed at night through a telescope. The various spots of light all look much alike. However, they are not all the same in character. Some may be caused by incandescent lamps, some by neon signs, some, perhaps, may be due to the newer type of yellow sodium lamp used for illuminating highways.

We now put a glass prism in front of the telescope objective. The telescope must be deviated sideways, if we are to see the city through the prism and the telescope. When we do see it, each spot of light appears to be smeared out into a band of color. The colors present in each spot of light are separated and spread out and we can see just what colors are present in the light from each source. The neon signs are characterized by definite colors in the orange and red; the sodium lamps can be recognized by the fact that only one color, yellow, is visible.

If we were to photograph the lights of an enormous city from an enormous distance the whole city would appear as a small, luminous spot. The prism would smear out the separate lights of which the spot is composed, but they would all be superposed in a single smeared spot for the whole city. However, if there were a large number of sodium lamps one point in the smear would be brighter than the rest because there would be an excess of the yellow sodium light.

A nebula, consisting of millions of suns a long distance away, behaves like our hypothetical city except for one small difference. Light from a sun has *dark*, absorption lines or bands, from which color is missing as a result of absorption in the sun's atmosphere. There is a dark line in the spectrum of our own sun, corresponding to absorption of hydrogen in the sun's atmosphere. This dark line always appears at the same place in the spectrum no matter what kind of a source, and always means that hydrogen is present. Dark lines appear in the nearer nebulae about where they should be in the spectrum. For the more distant nebulae, however, they are shifted towards the red end of the spectrum.

There is only one known explanation for such a shift of a spectral line. If the source is moving away from an observer the light received appears redder than when the source is stationary. This phenomenon is called the Doppler effect. It is a matter of common experience in the field of sound. The pitch of an automobile horn is lowered as the horn passes rapidly by an observer and recedes from him.

The photographs of the nebulae show that the hydrogen absorption line is shifted farther and farther away from the normal position as the pictures go to more and more distant nebulae. The amount of the shift gives the velocity of recession. Many nebulae have been observed and the conclusion is reached that for every million of light-years distance from the earth the velocity of recession is increased by about 100 miles per second. The farthest nebulae observed are flying away from us with a speed of about 25,000 miles per second.

It is well to weigh critically the evidence for results like these. As regards estimates of nebular distances the methods used by astronomers seem entirely adequate. In the nearest nebula individual stars can be seen. Some of these stars fluctuate in brightness with a period of 5⅓ days. Similar stars, known as Cepheid variables, are found in our own nebula and the distances of a few of them have been determined by ordinary engineering methods. It is found that these stars are all of about the same size, so that if one Cepheid variable is much fainter than another its faintness may be attributed solely to its greater distance. The distance of the nearest nebula can thus be determined with considerable accuracy by comparing the brightness of one of its Cepheid variables with the brightness of a similar star in our own galaxy—a star whose distance has been measured by reliable methods. Having a good estimate of the distance of one nebula it is legitimate to infer that other nebula of the same type are fainter and smaller only because they are farther away. It is thus possible to estimate their distances. The results of these estimates might give occasional large errors, but when a great number of observations are made the individual errors must average out fairly well.

As regards the shift of the absorption line towards the red, a good many attempts have been made to explain it in some other way than by the Doppler effect. So far, all of these attempts have failed or encountered logical difficulties. During the last few years, however, certain evidence has accumulated which has brought about a paradoxical situation in the theory of the expanding universe. There are some very serious objections to the theory. First, let us suppose that our explosion hypothesis is more or less in accord with the facts. After all, if the nebulae are now observed to be scattering they must at some previous time have been more closely bunched. It is not difficult to calculate how long ago it was when the nebulae were all together and touching each other. We know how far away they are now, we know how fast they are receding, and how their velocity of recession varies with the distance from us. These data enable us to calculate the time when they must have started. According to Hubble, after all corrections have been made this starting time was about 1000 million years ago. Unfortunately this is only a fraction of the age of the earth—indeed there is evidence that life actually existed on earth that long ago. It is difficult to see how our earth could exist in its present form at a time when all matter in the universe was assembled and ready for a cosmic blowout of such tremendous proportions.

So much for objection number one. The second objection arises as follows. When a source of light moves away from an observer there are two effects produced. The first, the Doppler effect, has been mentioned as a change of color, a reddening of the light. A second effect is a decrease of brightness, known as the "dimming factor." It is easy to see why a light should appear to be dimmer when the source moves away from the observer. Suppose a stationary machine gun is firing bullets at a fixed target at the rate of five per second. Then every second five bullets hit the target. However, if the gun is moving away from the target, still firing five shots a second, there will not be five bullets hitting every second. The bullet discharged from the gun at the end of a given second will have had to traverse a greater distance than the bullet which was fired at the beginning of the second, so it will take a longer time to reach the target. Perhaps only four bullets will hit the target in one second. The extra bullet has gone to fill the extra space in the bullet stream—the extra space created by the recession of the gun. The case of a light source is exactly analogous.

Now in estimating the distance of a nebula its brightness is taken as a criterion of the distance. The question arises as to whether the dimming factor should be applied when making the distance estimates. If the nebulae are actually moving away from us then the factor must certainly be applied. If the reddening of the light is not caused by a velocity of recession then the dimming factor must not be applied. With such tremendous speeds of recession this factor makes quite a big difference in results.

The following discussion is very largely quoted from the annual Sigma Xi lecture delivered in December, 1941, at Dallas by E. P. Hubble of the Mount Wilson Observatory. Dr. Hubble is one of the world's foremost authorities on the subject of nebulae.

Let us first suppose that the reddening of the light is *not* caused by a velocity of recession. It may be due to some hitherto undiscovered and unknown phenomenon. We can then estimate distances without any dimming factor and a survey can be made to find out how the nebulae are distributed throughout the region of space within our present range of view. Such surveys have been made at Mount Wilson and Mount Hamilton, out to a distance of 420 million light-years. Data have also been obtained and analyzed at Harvard, and the net result indicates a fairly uniform distribution of nebulae throughout the observable regions of space. There are, on the average, just as many per unit volume at great distances as in the immediate neighborhood of our own group.

This result is intellectually very satisfactory. In fact, it agrees with a fundamental principle of cosmological theory, a principle which has been postulated by theorists for no other reason than its appeal to our sense of order and the fitness of things. This principle states that the universe, on a grand scale, will appear much the same from whatever position in space it may be viewed, or explored. This principle of cosmology is satisfied, therefore, if the nebulae are not assumed to be receding.

We next investigate the consequences of assuming the red shift to be due to a real velocity of recession of the nebulae. The dimming factor must now be applied in estimating distances, with the result that the most distant cluster is actually about 13 per cent fainter than it would be if it were stationary. The scale of distances is thus altered, so that when we make our space survey to find out how the nebulae are distributed it turns out that they are no longer scattered uniformly. The number per unit volume increases steadily with their distance away from us. Here is a result which is intellectually very disquieting. The cosmological principle of no favored position is violated. We might be willing to accept this violation if it went the other way, that is, if the density of nebulae decreased with distance. Then we would conclude, very happily, that we had discovered another super-super-galaxy, another big matter bunch to put out on the right hand end of our linear layout. No such interpretation can be given when the nebulae are found not to thin out at big distances, but actually to become more dense in numbers.

It may seen obvious to the layman that we ought to discard the idea of an expanding universe. It makes us worry about the short time which has elapsed since the original cosmic explosion occurred; it bothers us with an increasing density of matter as we proceed farther and farther into the depths of space; and the only evidence we have to go on is a series of pictures, rather hazy, smeary pictures, in fact, with a light patch shifted too far to one side.

The physicist and the astronomer, unfortunately, cannot treat these fuzzy pictures in such a cavalier manner. There is no denying the existence of the shifted light patch in the pictures, hazy though it may be. There is no denying the fact that all such similar shifts of color have been explained satisfactorily by the Doppler effect and by the Doppler effect alone. One is reminded of the saying of the old colored man, whose years of experience had developed a certain ripe philosophy of life. "It ain't so much what you don't know that gets you into trouble, it's what you do know and ain't so!"

There are several ways, more or less unsatisfactory, of escaping from the dilemma of the expanding universe. The first way is not a good way, but like other escapist philosophies it must be considered and estimated for what it is worth. It involves spatial curvature.

The idea of curved space is now quite a familiar idea to most people. Eddington, Jeans, Einstein, and others have written books for popular consumption and the sales have been very gratifying. Even the pulp magazines do not hesitate to invoke the fourth dimension as a mode of escape for the hero or the villain. A simple way of approaching the concept of spatial curvature is as follows. Think of a straight line along one dimension. Given a second dimension at right angles to the first, then we have the possibility of curving the line into the second dimension. Think of a plane surface, like a sheet of paper flat on a desk. Given a third dimension, at right angles to the desk, we have the possibility of curving the paper sheet into this third dimension. Think of a solid filling three dimensions. Give a fourth dimension at right angles to the other three, we then have a possibility of curving the solid into the fourth dimension. It is only because we have three-dimensional minds that we cannot see this fourth dimension.

A mathematician may speak of space itself as being curved without reference to any solid matter in it. For example, consider the earth to be perfectly smooth. If we were two-dimensional creatures instead of being three-dimensional, we might draw a big circle on the earth's surface, measure its diameter and its circumference, and then find that the circumference was not equal to π times the diameter. We would not know that the circle was not flat (since we are assumed to be two-dimensional), but we could certainly infer a curvature of our flat space and even determine its radius if we knew enough about ordinary Euclidean geometry, which would work pretty well for small circles on the earth's surface.

The mathematical description of the universe to which allusion was made at the beginning of the lecture involved curving of three-dimensional space in somewhat the same fashion as described above for the two-dimensional space. If space actually is curved in this way our ordinary solid geometry, Euclidean geometry, would not be quite correct. In order to find out whether it is correct, measurements of certain kinds must be made. For example, if a negative parallax could ever be observed for a single star, a spherically curved space would be implied. The mathematician Schwarzschild, a good many years ago, attempted to find what curvature of space would be possible according to certain types of non-Euclidean geometry. In dealing with these geometries he said, "One there finds oneself, if one but will, in a geometrical fairyland, but the beauty of this fairy tale is that one does not know but that it may come true."

Schwarzschild's results need not be considered here because his data were limited and because we have at present more detailed modes of procedure than he used. There are at least two mathematicians who have achieved the unique distinction of having a universe named after them. They are Einstein, and a Dutchman named de Sitter. Both universes are non-Euclidean and the Einstein universe appears to be the more popular. The curvature of the Einstein universe is determined by the amount of matter in it, and if it is not a static universe, by certain other factors. A chunk of matter produces quite a large local curvature, which is evidenced to us by what we call gravitational attraction.

This universe is not infinite in extent. It is a closed universe with a finite volume but having no boundaries, just as the surface of a sphere is a closed surface of finite area yet has no bounding edges. In this universe one might expect to see a star in two directions, first by looking directly at it, second, by looking in the exactly opposite direction at light rays which have gone completely around the circuit of the universe in the opposite direction. Star images have not been seen in this way, possibly because their light is too faint after the long trip around the universe. There is also the possibility that the theory is wrong. It has, however, been seriously suggested that two very faint nebulae, observed in a certain direction, may actually be the backs of two of our nearest neighbors, as seen the long way around.

The theory of a finite, closed universe is very attractive in many respects. We may again use the term "intellectually satisfactory" in this connection, largely because this universe can be given a concise mathematical description and in terms that explain the gravitational effects of matter. There is also, in many individuals, a definite repugnance to the idea of infinite space. In discussing the stars Kant, in 1755, says, "There is here no end, but an abyss of real immensity in presence of which all the capability of human conception sinks exhausted." The finite mind likes to set up a blank wall somewhere, in order to end it all. It is probably intellectually satisfactory to know that one can start out in imagination and not have to get farther away forever and ever, but will eventually get back to the good, old, familiar region of the starting point.

With this picture of a finite, closed universe in mind we may now return to the question regarding the nebulae. Why should they appear to be crowded together at great distances from us? The answer might be that the curvature of space appears to make them crowd into smaller and smaller volumes as their distance increases. If this is true it is possible to calculate what radius of curvature of the universe would give the observed apparent crowding of the nebulae at great distances. Such calculations have been made and the universe turns out to be remarkably small. In fact, it is so small that our largest telescopes would allow us to see about one-sixth of the way around it. This small universe is required in order to explain the apparent non-uniform distribution of the nebulae. However, if we calculate the radius of the universe in this way we are obliged to have only a certain amount of matter in it, since, according to Einstein, the radius is determined by this total amount of matter. Hubble has made surveys to find out whether the observed amount of matter will fit in with the radius as determined above. He estimates that if all observable stars and nebulae were smeared out uniformly there would be a maximum of about one hydrogen atom per cubic meter. This density of matter is far too small. In other words, there is not enough matter in the universe to give it a curvature great enough to spread out the nebulae uniformly. The theory of curvature of space has, therefore, failed to resolve the problem.

Another way out of the dilemma is to suppose that the observations of the astronomers are in error. Here is what Hubble has to say. "These questions have been carefully reexamined during the past few years. Various minor revisions have been made, but the end results remain substantially unchanged. By the usual criteria of probable errors the data seem to be sufficiently consistent for their purpose. Nevertheless, the operations are delicate, and the most significant data are found near the limits of the greatest telescopes. Under such conditions it is always possible that results may be affected by hidden systematic errors. Although no suggestion of such errors has been found, the possibility will persist until investigations can be repeated with improved techniques and more powerful telescopes. Ultimately the problem should be settled beyond question by the 200-inch reflector destined for Palomar." This telescope will have about twice the range of the best one now in use. Work on it has been stopped by the war, so it is impossible to predict just how soon it can be put to work on this problem.

The last way which may be suggested for escaping from the dilemma is to suppose that in the region of astronomical magnitudes some new principle of nature is operative—some principle which we have not yet discovered in the ordinary macroscopic field. Such a principle would have to free us from the necessity of using the Doppler effect, and we would no longer have to say that experimental observation shows the universe to be expanding. This new principle would, therefore, have to explain why the light from nebulae gets redder and redder as it travels greater and greater distances. Perhaps light which has been travelling for 100 million years in a straight line exhibits its senility by a decrease in the frequency of its vibrations. We do not know of any possible reason such as this why old light should be different in any way from new light. The only place from which we can get really old light is from the distant nebulae, so our chances of establishing by experiment a new principle of physics like this seems at present to be involved in a vicious circle from which there is no escape.

It appears, therefore, that our knowledge of the structure of the universe at the limits of the astronomical range is unsatisfactory. We have to recognize that there are discrepancies between theory and experimental observations. Hubble says that "a choice is presented, as once before in the days of Copernicus, between a strangely small, finite universe, and a sensibly infinite universe plus a new principle of nature."

We may now go back once more for a comprehensive view of what we have called the linear layout of the universe in Fig. 1. The three components, or variables, were assumed quite simply to be space, matter, and time. At the right hand end of the scale we have become embroiled in some rather questionable speculations regarding the nature of space and the behavior of light. In this region, where a light-year is the unit of distance and a nebula the unit of mass, we have good reason for suspecting that the mechanics of the universe cannot be described or explained in such a simple way as in the region of miles and mountains.

Peculiarly enough, if we go from the enormously great region to the extremely small region, the region of the electron and the positron, we encounter similar difficulties. You will remember that Darrow characterized the microscopic region as unique because "of the adventurous excursions of the observers," and "the grandeur of the inferences." One or two of these inferences and excursions may be cited here, and it will appear that the simple concepts of space and matter have suffered in the microscopic field in much the same way that they have suffered in the astronomical field. As the result of investigations in the field of the small particles it has become necessary to broaden our ideas as to the nature of matter. Cloud chamber pictures have allowed us practically to see two particles of matter created in space from the energy contained in radiation.

The thing that happens is that a photon, an atom of radiant energy travelling with the speed of light, somehow gets itself into a peculiar situation in a microscopic field of some kind. The result is that the photon changes into two particles with electric charges, a positron and an electron.

In the macroscopic size range an equivalent phenomenon would be for a quantity of sunshine, passing by an iron ball, to change suddenly into a couple of buckshot.

Needless to say, no one has ever seen anything like this happen. It is only when sizes become so small as to prevent direct observation that the event occurs. We may well say that something peculiar is going on in the microscopic field. Something is happening which is foreign to our ordinary experience.

Technically this phenomenon is known as pair production by a photon. The reverse process, conversion of matter into radiation, can occur when an electron and a positron come together under proper conditions. They disappear and two photons of radiation are shot out with the speed of light in opposite directions.

Matter and energy can now be thought of as practically synonymous. It thus becomes possible to make certain grand inferences with the object of saving the universe from running down. Millions of suns are slowly but surely converting their matter and their energy into radiation and this radiation is constantly escaping into infinity. Perhaps, somewhere in space, radiation may be changed back into matter. Perhaps the universe is engaged in a reversible cycle, instead of an irreversible one, as is commonly supposed.

As an illustration of what Darrow calls an "adventurous excursion" of an observer we may take the Dirac theory of the positron. Dirac is a brilliant young Englishman, a mathematician who has demonstrated a high degree of daring and originality in his handling of theoretical physics.

His theory of the positron starts out with two peculiar assumptions. First a particle may have a negative kinetic energy. Second, all space is filled with particles of negative kinetic energy. There is a distribution of electrons of infinite density everywhere in the world. A perfect vacuum is a region where all the states of positive energy are unoccupied and all those of negative energy are occupied.

When an electron, by some means or other, gets knocked out of this state of negative energy into a state of positive energy, it is observed as an ordinary electron; the hole which was left is a positron. This hole may wander around for a short time, but there are so many more electrons in the universe than holes that it is not long before some electron drops into the hole and both hole and electron disappear from the view of normal people. The very short life of the positron is thus explained, as is also the phenomenon of pair production and the conversion of matter into radiation.

I have given this hasty outline of the theory, not that I expect anyone to understand it—it is hardly to be expected that negative energy can be understood—but because it illustrates the lengths to which a theorist has to go in creating physical explanations in this field. In the microscopic range of sizes a quite perfect explanation of things is given by a specialized type of mathematics called wave mechanics. It is only when this mathematical symbolism is explained in terms of physical symbolism that we call it an adventurous excursion. Dirac showed great courage in even trying to give a physical picture of his mathematical theory. The fact is that in the microscopic field things may behave in a way entirely foreign to the way in which we have always seen large objects behave, hence they cannot be explained in the old familiar ways.

There is in most people a strong tendency to label as "bunk" that which is not understood. This tendency is, on the whole, a healthy one. Skepticism is preferable to credulity if one is thinking in terms of the struggle for existence. The radio-listeners who believe all the remarkable statements made about cough-syrups, breakfast foods, cigarettes, etc., must certainly be struggling very hard for existence. However, skepticism based upon a lack of understanding is a dangerous attitude of mind. Professor P. W. Bridgman of Harvard, has this to say in his book, *The Logic of Modern Physics:*

"It is difficult to conceive anything more scientifically bigoted than to postulate that all possible experience conforms to the same type as that with which we are already familiar, and therefore to demand that explanations use only elements familiar in everyday experience. Such an attitude bespeaks an unimaginativeness, a mental obtuseness and obstinacy which might be expected to have exhausted their pragmatic justification at a lower plane of mental activity."

The explanation of microscopic phenomena, then, utilizes concepts which are not familiar to everyday experience. For that reason the microscopic tends to undermine any smug complacency we may have regarding our knowledge of nature and the universe. Take, for example, the Heisenberg uncertainty principle. This principle states that we can never know accurately both the position and the velocity of a small particle. It is easy to see why this is true. We can see the small particle because light has bounced off of it into our eye. We see it in the direction from which the light bounced.

But the light, in bouncing from the particle, must have given it a push so that either its position or its velocity will have been changed by the mere fact that light must be used to observe it. By the time the light photon gets to the eye of the observer the particle will not be at exactly the spot from which the photon appeared to bounce.

This uncertainty principle has been given an exact mathematical formulation. It turns out that if the position of an electron is known to within 0.004 inch then the speed of its motion is uncertain to within about 3 feet per second—the speed of a slow walk.

The tendency, at first, is to consider this as rather a superficial principle. I can easily imagine a particle to have both position and momentum simultaneously; why bother so much about a mechanism for determining them? However, a thorough study of the situation, with an analysis of every conceivable means afforded by nature for making determinations, impresses one with a feeling that here is a conspiracy of nature to prevent man from acquiring too much detailed information. A conspiracy of nature is a law of nature; we cannot pass it over as being of no importance. It is as if nature had erected a wall of impenetrability around the smallest particles and forced us to see them only partially, as if through cracks in the wall.

It appears, therefore, that we are asking a meaningless question when we ask just where an electron is when it has a certain definite momentum. No possible operation can be thought of by which an answer to this question can be secured without violating a law of nature. The conclusion is that the electron cannot have an exact velocity and an exact momentum simultaneously. There is an essential fuzziness in the very foundations of nature herself. Time and space are a little peculiar in the microscopic region, most certainly.

Someone has said that "the infinite, whether the infinitely large, or the infinitely small, seems to carry disaster in its wake." I do not think the word disaster is happily chosen in this connection. It is true that the two infinities at either end of our linear layout have shattered the beautiful, crystal-clear mechanical system which described the universe during most of the nineteenth century—when the luminiferous ether was as definitely material as a piece of iron, and when a scientist could say that practically all pioneer research in physics was over and nothing remained except to measure things with increasing accuracy. This complacent attitude is fortunately gone forever, and the two infinities have had a great deal to do with its disappearance. The new problems presented, the paradoxes, the uncertainties, all combine to give us a picture of modern science once more struggling, once more growing. It seems better to change the quotation to read, "The infinite, whether the infinitely large or the infinitely small, seems to have carried renaissance in its wake."

In summing up the subject we may say that the small part of the universe, open to everyday experience, has given us a simple conception of nature, a simple body of laws, which seems unable to cope with problems either in the region of the super-nebulae or in the region of the extremely small particles.

In the latter field we have found that, properly speaking, descriptions of phenomena must be mainly mathematical. Such descriptions are quite adequate at present, and we feel that the main problems of explanation are well in hand. But we must be careful not to expect the same type of explanation that is used for objects of ordinary size, and we must remember that here there is a certain indefiniteness of behavior. We do not say that a small particle can *never* get over a high hill when it does not have enough energy to carry it to the top. We say that the probability of its getting over is small. It actually has a small probability of doing the job with an insufficient amount of energy!

In the region of the super-nebulae we are at present up against a paradox. We are at liberty to suppose that space is of a peculiarly curved character, or that it goes on to infinity; that the super-nebulae are flying away with enormous velocities, or that some unknown principle of nature is deceiving us. We may be affected by a feeling of futility because of this state of affairs, and even have a sympathetic feeling for St. Ambrose, who in 389 A.D. wrote: "To discuss the nature of the earth does not help us in our hope of the life to come. It is enough to know that Scripture states that He hung up the earth on nothing. Why argue whether He hung it up in air or on water? The majesty of God constrains it by the law of His will."

The spirit of modern science is not in agreement with St. Ambrose, and is not to be discouraged by apparent contradictions. This spirit demands continual arguing and speculating as to how the universe is hung up. Certainly we will always see as through a glass darkly, but just as certainly we will always keep on trying to polish the glass.

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